

Suppression of Spin Relaxation in Submicron InGaAs Wires

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We investigate electron spin dynamics in narrow two-dimensional n -InGaAs channels as a function of the channel width. The spin relaxation times increase with decreasing channel width, in accordance with recent theoretical predictions based on the dimensionally-constrained D'yakonov-Perel' mechanism. Surprisingly, the suppression of the relaxation rate, which is anticipated for the one-dimensional limit, is observed for widths that are an order of magnitude larger than the electron mean free path. We find the spin precession length and the channel width to be the relevant length scales for interpreting these results.

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In the emerging field of spintronics, it is important to explore carrier spin relaxation mechanisms in nanostructures as a function of dimensionality. The effect of reducing feature sizes in spintronic devices is relevant for future technological applications [1, 2]. In two and three dimensions, elementary rotations do not commute, with significant impact on the spin dynamics if the spin precession is induced by spin-orbit coupling [3]. Spin-orbit coupling creates a randomizing momentum-dependent effective magnetic field; the corresponding relaxation process is known as the D'yakonov-Perel' (DP) mechanism [4]. In an ideal one-dimensional system, however, all spin rotations are limited to a single axis, and the spin rotation operators commute. In the regime approaching the one-dimensional limit, a progressive slowing and finally a complete suppression of the DP spin relaxation have been predicted, if the lateral width of a two-dimensional channel is reduced to be on the order of the electron mean free path [5, 6, 7, 8]. The predictions are made for semiconductor heterostructures, such as InGaAs quantum wells, in which the spin-orbit interactions are dominated by structural inversion asymmetry (SIA) [9, 10, 11, 12]. Such solid-state systems have been proposed as candidates for spintronic devices, including spin transistors [13], due to their potential scalability and compatibility with existing semiconductor technology.

Here, we combine optical time-resolved Faraday rotation (TRFR) spectroscopy with magnetotransport measurements in two-dimensional, n -doped InGaAs quantum well channels. As a function of the channel width, we extract the spin relaxation time and the elastic scattering times of the electrons. Surprisingly, experiments on wide channels, with widths of an order of magnitude larger than the electron mean free path l_e , reveal an effective slowing of the spin relaxation. In this regime, the data show that the spin relaxation is dominated by the DP

mechanism. For narrower channels, we find that an interplay between the spin precession length l_{SP} and the channel width w determines the electron spin dynamics in the wires. A saturation of the slowing spin relaxation is found for the narrowest wires, indicating other sources of spin relaxation exist such as the cubic spin-orbit coupling term due to bulk inversion asymmetry (BIA) [14] and the spin relaxation mechanism proposed by Elliot and Yafet [15].

The spin splitting in a two-dimensional quantum well due to SIA can be expressed in the form of an effective angular frequency vector

$$\mathbf{\Omega}(\mathbf{k}) = (1/l_{SP})[\mathbf{v}(\mathbf{k}) \times \hat{z}] \quad (1)$$

with \mathbf{k} the momentum vector, and $\mathbf{v}(\mathbf{k})$ the velocity of an electron [2]. \hat{z} is the unit vector perpendicular to the quantum well, and l_{SP} is the spin precession length, over which the electrons remain spin polarized. Given a system with a fixed mean free path, a larger effective angular frequency induces faster spin rotations and, in turn, a shorter spin relaxation time. In the case of motional narrowing [16], the corresponding spin relaxation rate can be described as

$$\tau_{SP}^{-1} = |\mathbf{\Omega}(\mathbf{k})|^2 \tau_M / 2 \quad (2)$$

with τ_M the momentum scattering time. In order to probe the spin dynamics for different momentum vectors, transport and spin coherence experiments are performed on a set of n -doped InGaAs wires [Fig. 1(a)]. Wires are patterned along the crystallographic directions [100], [110], [010] and $\bar{1}10$, while the spins are optically oriented along the growth direction [001]. Structures are fabricated by e-beam lithography and reactive ion etching out of three modulation-doped n -In_{0.2}Ga_{0.8}As/GaAs quantum wells. The unpatterned quantum wells A, B, and C have the following sheet densities n_s and mobilities at a temperature of $T = 5$ K: (A) $5.4 \times 10^{11} \text{ cm}^{-2}$ and $3.8 \times 10^4 \text{ cm}^2/\text{V s}$, (B) $6.6 \times 10^{11} \text{ cm}^{-2}$ and $3.1 \times 10^4 \text{ cm}^2/\text{V s}$, and (C) $7.0 \times 10^{11} \text{ cm}^{-2}$ and $2.4 \times 10^4 \text{ cm}^2/\text{V s}$. The quantum wells are situated 100 nm below

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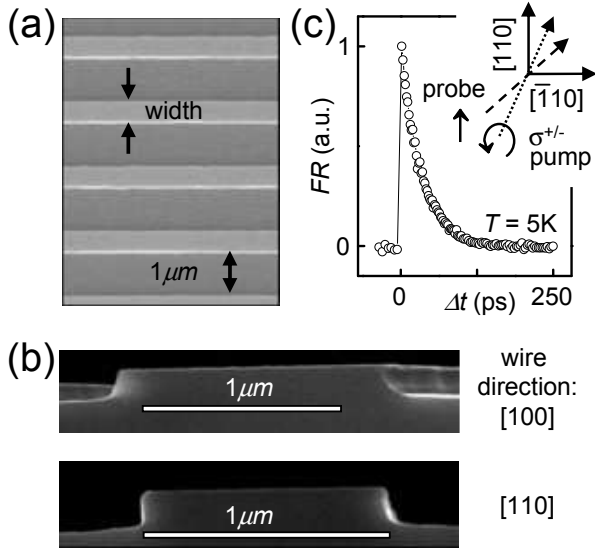


FIG. 1: (a) Scanning electron micrograph (SEM) of dry-etched InGaAs wires, which are patterned along the four crystallographic directions [100], [110], [010], and $\bar{1}\bar{1}0$. The wire widths are varied between 420 nm and 20 μm , while the separation is fixed at 1 μm . (b) SEM of Sample A along the $\bar{1}\bar{1}0$ cleaving direction. Both wires along [100] and [110] have a width of $(1.02 \pm 0.04) \mu\text{m}$. (c) Time-resolved Faraday rotation (TRFR) of 750 nm wires patterned along [010] on Sample A at zero magnetic field. Inset: a circularly-polarized pump pulse excites the spin polarization. A time-delayed linearly-polarized pulse probes the spin dynamics.

the surface of the heterostructures, and the quantum well width is $\Delta z = 7.5 \text{ nm}$ (for more details on the growth, see Ref. [17]). The widths of the wires w range between 420 nm and 20 μm , and the height of the wires is chosen to be 150 nm [Fig. 1(b)]. For the optical experiments, the wires are arranged in arrays with the dimension of $200 \times 200 \mu\text{m}^2$, while the diameter of the laser spot is about 50 μm . In order to provide constant etching parameters for all widths and directions of the wires, the distance between adjacent wires is set to be 1 μm for all of the arrays. Magnetotransport experiments are performed on single wires fabricated with the same etching parameters [18].

The electron spin dynamics are probed with the TRFR technique, using 100 fs pulse trains from a mode-locked Ti:Sapphire laser tuned to the absorption edge of the quantum wells, $E_{\text{LASER}} = 1.37 \text{ eV}$ [Fig. 1(c)] [17]. The evolution of the Faraday rotation angle can be described by a single exponential decay $\Theta_F = A_1 e^{\Delta t / \tau_{\text{SP}}}$, where A_1 is the amplitude of the electron-spin polarization and Δt is the time delay between the circularly-polarized pump and the linearly-polarized probe pulse. As shown with solid lines in Fig. 2(a), the exponential behavior of the data is described by a longitudinal spin relaxation time τ_{SP} for both the unpatterned quantum well (open squares) and for the wires aligned along different crystal-

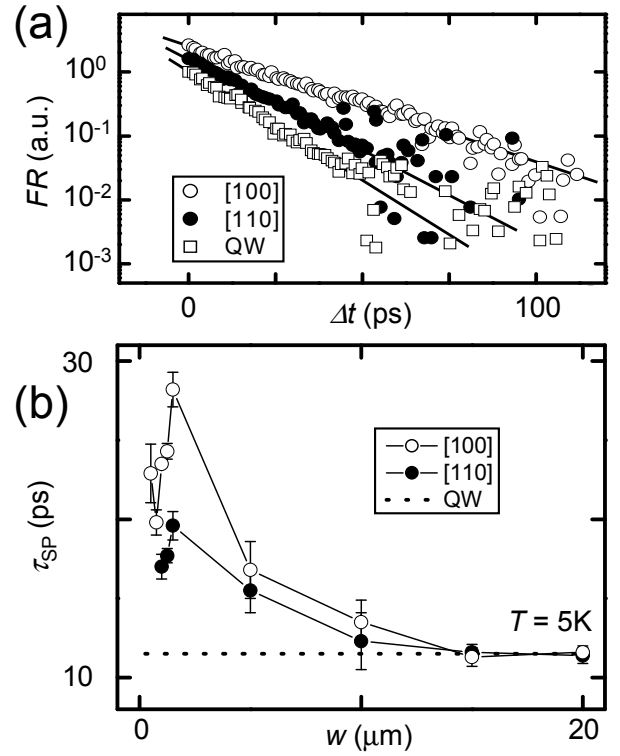


FIG. 2: (a) Faraday rotation at 5 K for Sample B (open squares) and 750 nm wires patterned along [100] (open circles) and [110] (filled circles). Black lines are guides to the eye, and the data are off-set for clarity. (b) Width dependence of spin relaxation times for wires fabricated from Sample C. The dotted line depicts the spin relaxation time of the unpatterned quantum well. Measurements were performed at $B = 0$.

lographic directions (data for Sample B at 5 K) [19]. For all samples, we find that at widths narrower than $\sim 10 \mu\text{m}$, the spin relaxation times in the wires are longer than in the unpatterned quantum wells [Fig. 2(b)]. In addition, we find that wires aligned along [100] and [010] show equivalent spin relaxation times, which are generally longer than the spin relaxation times of wires patterned along [110] and $\bar{1}\bar{1}0$ (for clarity, only the data for the directions [100] and [110] are shown). All data are obtained by measuring the transmission signal in the Faraday geometry.

If an external magnetic field is applied perpendicular to the quantum wells, the precession axis of the electron spin can be fixed independently of the scattered momentum vector. In the case that the DP mechanism is the dominant relaxation process, the following magnetic field dependence of the spin relaxation time has been predicted (for $\omega_C \tau < 1$) [20]:

$$\tau_{\text{SP}}(B) = \tau_{\text{SP}}(0)[1 + (\omega_C \tau)^2] \quad (3)$$

where $\omega_C = eB/m^*$ is the cyclotron frequency of an electron with charge e , $m^* = 0.064 m_e$ is the effective electron mass [17], and τ represents the intrinsic elastic scattering

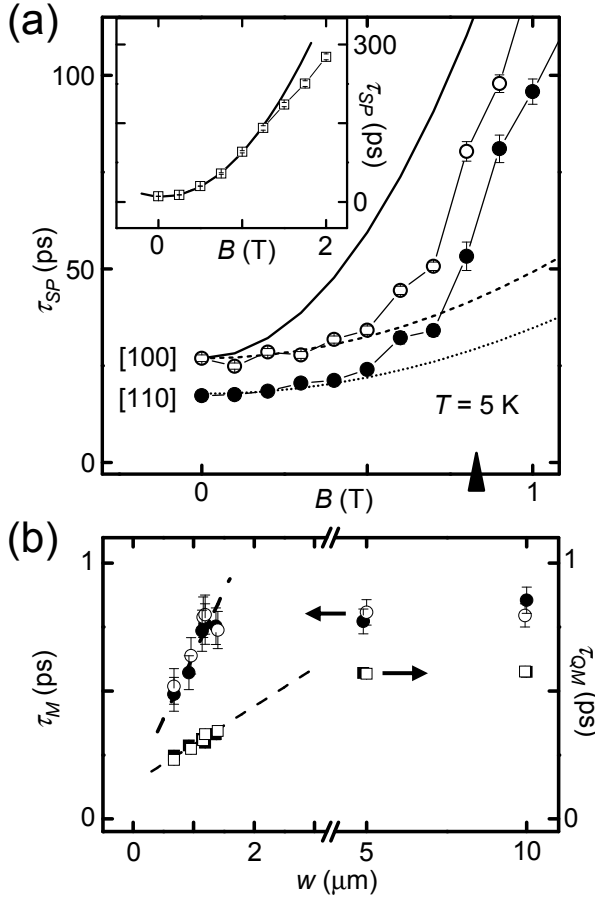


FIG. 3: (a) Magnetic field dependence of spin relaxation times in the unpatterned Sample C (inset) and wires (open and filled circles for [100] and [110], respectively). The magnetic field is applied perpendicular to the surface of the sample. The dotted, dashed, and black lines are fits to Eq. (3), and the triangle indicates B_{QM} (see text for details). (b) Momentum scattering time (circles) and quantum lifetime (squares) versus channel width for the directions [100] (open symbols) and [110] (filled symbols), respectively. The dashed lines are guides to the eye.

time. The magnetic field dependence of the spin relaxation time for the unpatterned quantum wells is well fit by this prediction [Fig. 3(a), inset]. We find that $\tau \sim 1$ ps, in agreement with the measured momentum scattering time τ_M in these quantum wells [17]. Figure 3(a) displays τ_{SP} as a function of magnetic field for wires with $w = 1.25 \mu\text{m}$ patterned on wafer C. The solid line shows the prediction according to Eq. (3) with a momentum scattering time of $\tau_M = (7.6 \pm 0.2) \times 10^{13}$ s. In addition, we determine an estimate of the quantum lifetime τ_{QM} through magnetotransport measurements on single wires by plotting the Shubnikov-deHaas oscillations in a Dingle plot [21]. Surprisingly, the optical data is better fit using the quantum lifetime $\tau_{QM} = (3.1 \pm 0.1) \times 10^{-13}$ s (dashed and dotted lines for the directions [100] and [110], respectively). The condition $\omega_C \tau_{QM} = 1$ can

be represented by a magnetic field $B_{QM} = m^*/e\tau_{QM}$, which is depicted as a triangle. It can be nicely seen that Eq. (3) describes the data well for $\omega_C \tau_{QM} < 1$. This field-dependence of τ_{SP} suggests that (i) the DP mechanism is indeed the dominant spin relaxation mechanism in the studied structures and (ii) the quantum lifetime τ_{QM} is the relevant time scale for the wires at low magnetic field values where the Zeeman energy is negligible.

Figure 3(b) shows the dependence of τ_M and τ_{QM} on the channel width. Both scattering times show a rapid decrease for the narrowest channels. Since the spin relaxation times greatly exceed the charge scattering times, the quantum wells can be considered to be in the "motional narrowing" regime [Eq. (2)] [16]. Figure 3(b) further demonstrates that τ_M is constant for wires with $w \geq 1.2 \mu\text{m}$, independent of the crystallographic direction (the value of the momentum scattering time corresponds to a mean free path $l_e = (275 \pm 5)$ nm). In Fig. 2(b), however, we find an enhanced spin coherence for wires with $w \leq 5 \mu\text{m}$. This implies that for $1.2 \mu\text{m} \leq w \leq 5 \mu\text{m}$, the effective angular frequency $|\Omega(\mathbf{k})|$ is reduced, according to Eq. (2). At the same time, we observe from the images shown in Fig. 1(b) that the channels are homogeneously etched. Consequently, strain relaxation in the quantum wells via dislocation nucleation is unlikely for wires with $1.2 \mu\text{m} \leq w \leq 5 \mu\text{m}$ and a quantum well width of $\Delta z = 7.5$ nm [22]. This interpretation is supported by the fact that the two-dimensional electron density n_S in the channels shows no dependence on the channel width and direction down to $w \sim 400$ nm.

Figure 4(a) shows the ratio between the wire width w and the spin diffusion length

$$l_{SD} = \sqrt{\tau_{SP} \cdot v_F^2 \tau_M / 2} \quad (4)$$

as a function of w . In the motional narrowing regime, the spin diffusion length is the same as the spin precession length; inserting Eq. (2) into Eq. (4) yields $l_{SD} = v_F / |\Omega(\mathbf{k})| = l_{SP}$. For wide channels, the spin precession/diffusion length is given by the two-dimensional limit, i.e. a linear dependence of w/l_{SP} versus w (dashed line). For narrow widths, however, the data suggest that the spin diffusion length is ultimately limited by the wire width ($w/l_{SP} \sim 1$) [Fig. 4(a), inset]. Concerning the spin diffusion length, the narrowest wires act as quasi one-dimensional channels and, in turn, the two-dimensional spin dynamics are constrained by the side walls of the wires [5, 6, 7, 8]. Figure 4(b) depicts the ratio of τ_{SP} and τ_{QM} as a function of the mean free path l_e in a logarithmic scale. A qualitatively similar graph is obtained using τ_M instead of τ_{QM} . The graph closely resembles the predictions of Ref. [7], which indicates that the slowing of the spin relaxation in the wires is due to a dimensionally-constrained DP mechanism, as predicted for SIA [5, 6, 7, 8]. The DP spin relaxation due to BIA eventually limits this slowing [6]. An anisotropy

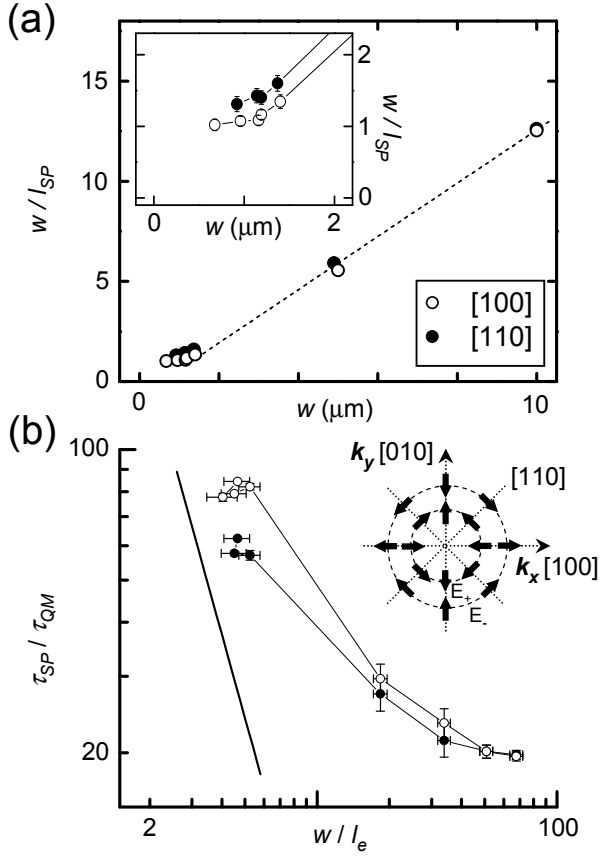


FIG. 4: (a) Ratio of the channel width w and the spin diffusion length l_{SP} as a function of w . Inset: For narrow wires, the channel boundaries limit the spin diffusion length. (b) Logarithmic presentation of the spin relaxation time in units of the scattering time and the mean free length. Black line depicts the quasi one-dimensional limit (open and closed circles for [100] and [110], respectively). Inset: Schematic vector map of the spin eigenfunctions in a quantum well with bulk inversion asymmetry.

in the spin-splitting and, thus, in $|\Omega(\mathbf{k})|$ has been predicted for InGaAs quantum wells assuming cubic BIA terms and Fermi wave vectors which are comparable to $k_F = \sqrt{2\pi n_S} \cong (0.018 - 0.021) \text{ \AA}^{-1}$ of the discussed samples [14]. Since the spin splitting due to BIA is anisotropic, the magnitude of $|\Omega(\mathbf{k})|$ depends sensitively on the momentum vector. This explains why spin lifetimes are similar for channels oriented along [100] and [010], but are different from wires patterned along the [110] and $\bar{1}10$ directions. The inset of Fig. 4(b) depicts the orientation of the spin eigenfunctions for two spin-split subbands E_+ and E_- of a zincblende quantum well in the presence of BIA (E_+ and E_- are defined as in Ref. [14]). For SIA, however, Eq. (1) suggests a constant value of $|\Omega(\mathbf{k})|$ that only depends on the magnitude of \mathbf{k} and which is always oriented perpendicular to \mathbf{k} . For the narrowest channels, the data do not reach the predicted behavior of $\tau_{SP} \sim w^{-2}$ [black line in Fig. 4(b)], where

the channel width would limit the mean free path [6, 7]. Instead, we find a saturation of the spin relaxation time. Since the Elliott-Yafet mechanism becomes more effective for shorter scattering times, this relaxation mechanism ultimately limits the slow-down of the spin relaxation in the narrowest channels [15]. At the same time, a negligible pump power dependence of the TRFR data supports the interpretation that the spin relaxation mechanism proposed by Bir, Aronov, and Pikus is only of minor importance to the spin dynamics in the InGaAs wires [23].

Generally, we utilize InGaAs quantum wells with a relatively low In concentration and an electron mobility $\mu \cong (2 - 4) \times 10^4 \text{ cm}^2/\text{V s}$. The spin precession length $l_{SP} \cong (0.9 - 1.1) \mu\text{m}$ [Fig. 4(a)] yields a Rashba spin coupling constant of $\alpha \equiv \hbar^2/(2l_{SP}m^*) \cong (0.5 - 0.7) \times 10^{-12} \text{ eV m}$ [2, 7], in good agreement with previous results on InGaAs quantum wells [10, 24]. This set of parameters ensures that the quantum wells are in the "motional narrowing" regime, in order to detect the dimensionally-constrained DP mechanism [5, 6, 7, 8]. Coupling constants of $\alpha \cong 4 \times 10^{-11} \text{ eV m}$ have been achieved by increasing the In concentration in the quantum wells [9, 11, 13, 24]. Larger coupling constants entail relatively short spin precession lengths and thus shorter spin relaxation times, which can be compensated by lowering the electron mobility.

In summary, an effective slowing of the D'yakonov-Perel' (DP) spin relaxation mechanism is observed in unexpectedly wide conducting channels of n -InGaAs quantum wires. The results are consistent with a dimensionally-constrained DP mechanism as recently predicted for narrow two-dimensional quantum wells exhibiting structural inversion asymmetry. For the narrowest wires with only a few hundreds of nanometers width, an interplay between the spin diffusion length and the wire width determines the spin dynamics.

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